VLA Observations of the "Eye of the Tornado"- the High Velocity H II Region G357.63−0.06

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ABSTRACT

The unusual supernova remnant candidate G357.7−0.1 and the compact source G357.63−0.06 have been observed with the Very Large Array at 1.4 and 8.3 GHz. The H92α line (8.3 GHz) was detected from the compact source with a surprising velocity of ~ -210 km s^{-1} indicating that this source is an H II region, is most likely located at the Galactic center, and is unrelated to the SNR. The H I absorption line (1.4 GHz) data toward these sources supports this picture and suggests that G357.7−0.1 lies farther away than the Galactic center.

Subject headings: ISM: individual(G357.63−0.06) — supernova remnants – HII regions

1. INTRODUCTION

The unusual and intense radio source G357.7−0.1, the Tornado, has been the subject of controversy since it was first recognized by Milne (1970) (**?**, also see)]Caswell1980,Caswell1989, Shaver1985a,Weiler1980. The Tornado has a non-thermal spectrum ($-0.5 \lesssim \alpha \lesssim -1.0$) and is polarized (Stewart et al. 1994). The morphology of the Tornado is unique among galactic sources and it has been suggested that the source is extragalactic, a SNR (supernova remnant), or a member of a new class of galactic head tail sources related to W50 and SS443 (Becker & Helfand 1985; Helfand & Becker 1985). The discovery of a collisionally pumped OH (1720 MHz) maser near G357.7−0.1 by Frail et al. (1996) has renewed suggestions that the source could, in fact, be a SNR. Using the Zeeman effect, Brogan et al. (2000) observed a magnetic field of 0.7 μG in the OH maser.

The nature of the flat spectrum, compact source G357.63−0.06 at the western extreme of the Tornado has been also controversial. It has been suggested that the source could contain a pulsar and might be a pulsar wind nebula physically related to the possible SNR

G357.7−0.1 (Shull, Fesen, & Saken 1989). These authors raise the possibility that this putative pulsar might be interacting with the supernova shell and be responsible for the unusual morphology of G357.7−0.1, similar to CTB 80. Alternatively, Shaver et al. (1985b) have summarized evidence that the source is an H II region that may be unrelated to G357.7−0.1. As suggested by Brogan et al. (2000), higher resolution radio continuum and recombination line observations of G357.63−0.06 were necessary in order to determine if the source is an H II region, as had been suggested by its flat radio spectrum. In the following, all references to the "Tail", "Head", and "Tornado" refer to the supernova remnant candidate G357.7−0.1, while the "Eye" refers to the compact source G357.63−0.06. Figure 1 shows a 21 cm image created from archival VLA data with $\sim 12''$ resolution in which the Tail and Head of the Tornado and the Eye are identified for reference.

A search for radio recombination lines (RRL) toward G357.63−0.06 (the Eye) was begun in 2000 using the NRAO[1] Very Large Array (VLA). After several unsuccessful searches covering the velocity range of the OH maser (-12.3 km s^{-1}) in 2000, we learned of a detection of a Brγ line at high negative velocities using the Anglo-Australian Observatory by Burton et al. (2002). We subsequently detected the H92α line at the surprising velocity of -210 km s^{-1} with the VLA in 2001. In order to better constrain the distances of the Tornado and the Eye, in 2002 we also observed the H I line in absorption with the VLA toward these sources.

2. OBSERVATIONS

The VLA observations of 2000 and 2001 of the H92α (8.309 GHz) line are summarized in Table 1. The initial observations in June and July 2000 only cover the velocity range -100 to 60 km s^{-1}, and are centered at -12.3 km s^{-1}, the velocity of the OH maser detected by Frail et al. (1996). The wider band width observations of late 2000 (also centered at -12.3 km s^{-1}) cover the velocity range of -195 to $+190$ km s^{-1}. The data obtained in 2001 were made with a more favorable center velocity (-200 km s^{-1}) and include the range -400 to 0 km s^{-1}. We also observed the H I line at 1.42 GHz in absorption toward the Tornado, and the parameters of these observations are also given in Table 1. In addition, the parameters of the archival 1.4 and 4.9 GHz continuum data used in our analysis are also shown in Table 1. All of these data were reduced in the usual fashion using the AIPS (Astronomical Image Processing Software) package. The H92α and H I spectral line data were Hanning smoothed

[1]The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc.

and their spectral resolutions can also be found in Table 1. Subsequent spectral line Gaussian fitting and spatial integration were carried out using GIPSY[2].

3. RESULTS

In Figure 2, we show VLA 8.3 GHz continuum images of the Head (G357.7−0.1) and Eye (G357.63−0.06) from the combined 2000 data and line free channels of the 2001 data. The Head image was created from UV spacings less than 100 kλ (to achieve good image quality and sensitivity to the extended emission) and its resolution is $14\farcs3 \times 6\farcs8$. The image of the Eye has a resolution of $3\farcs1 \times 2\farcs1$ and it was obtained by including all of the longer baselines up to 350 kλ. The position of the Eye is RA = $17^{\rm h}40^{\rm m}05\fs68 \pm 0\fs01$, DEC = $-30^\circ58'56\farcs1 \pm 0\farcs1$ (J2000). It is clear from this high resolution image that G357.63−0.06 is not spherically symmetric or of uniform brightness, and its morphology is most likely shell type (see also Burton et al. 2002). Both images yield a total flux and size for the compact source, G357.63−0.06 of $\sim 88 \pm 2$ mJy beam^{-1} and $\sim 6''$, respectively. The results from the 8.3 GHz images along with the parameters derived from the line-free 1.4 GHz H I data, archival 1.4 GHz data (also see Fig. 1), and archival 4.9 GHz data are listed in Table 2.

For the 8.3 GHz H92α line data of 2001 alone (beam $14.9'' \times 6.6''$), the rms noise is 0.4 mJy beam^{-1} and the peak of the G357.63−0.06 continuum is 57.6 mJy beam^{-1}. In Figure 3, we show the H92α spectrum toward the peak of G357.63−0.06. Based on a Gaussian analysis, the line parameters are: $v = -210 \pm 3$ km s^{-1}, $\Delta V = 36 \pm 7$ km s^{-1}, and the line to continuum ratio is 0.042 ± 0.007.

Figure 4 shows integrated, continuum weighted H I spectra from the Head and Eye of the Tornado. Both spectra clearly show the 3 kpc arm of the Galaxy at ~ -60 km s^{-1}, as well as a number of other distinct features at about −94, −30, −10, +10, and +45 km s^{-1}. Interestingly, the H I spectrum toward the Head also shows weak absorption near −210 km s^{-1} (inset in Fig. 4). The H I spectrum toward the Eye itself is of insufficient signal to noise to detect the weak −210 km s^{-1} feature.

[2]The Groningen Image Processing System (GIPSY) is documented at `http://www.astro.rug.nl/~gipsy/`.

4. DISCUSSION

4.1. Distances

It is certain that both the Eye and the body of the Tornado are at a distance greater than 5 kpc since H I spectra toward both sources (Fig. 4) clearly show the 3 kpc arm of the Galaxy at ~ -60 km s^{-1} (**?**, also see)]Rad1972. The detection of a RRL toward the Eye is unequivocal evidence that G357.63−0.06 is an H II region. The surprisingly high velocity of this H II region ~ -210 km s^{-1} implies that it is kinematically well separated from the OH (1720 MHz) maser discovered by Frail et al. (1996) located $\sim 1.4'$ to the NE of the Eye at a velocity of $v = -12.3$ km s^{-1} (see Fig. 2). If the OH (1720 MHz) maser is associated with the Head of the Tornado as inferred by Frail et al., the location of G357.63−0.06 along the symmetry axis of the Tornado (see Fig. 1) must be viewed as a chance superposition along the line of sight in agreement with the suggestion of Stewart et al. (1994).

It is likely that G357.63−0.06 lies close to the Galactic center, most likely in the Nuclear disk as this is the only place where such high negative Galactic rotation velocities (~ -200 km s^{-1}) are found (**?**, e.g.)]Burton1978,Liszt1980,Dame1987, Dame2001. If we assume this is the case, the minimum projected distance of this H II region from Sgr A is ~ 350 pc. Similar velocities of ~ -200 km s^{-1} have been observed $\sim 1^\circ$ NE of G357.63−0.06 towards the SgrE H II region complex via radio recombination lines by Cram et al. (1996) and Lockman, Pisano, & Howard (1996). The CO $b - v$ and $\ell - v$ diagrams of the Galactic center region from Bitran et al. (1997) show a resolved clump of CO emission about 0.5° in extent at $\ell \sim 357.7^\circ$, $b \sim -0.1^\circ$ and $v \sim -210$ km s^{-1}, confirming the presence of molecular gas in the vicinity of G357.63−0.06 (**?**, see also)]Burton2002. CO observations by Shaver et al. (1985b) toward the Eye also show a feature at 9 km s^{-1}, but this component is most likely related to a foreground molecular cloud, and is not associated with G357.63−0.06.

Our new high dynamic range, integrated H I absorption spectrum towards the Head of the Tornado (Fig. 4) also reveals for the first time an absorption feature at ~ -210 km s^{-1}. The detection of this component unambiguously places the Tornado at least as far away as the Galactic Center distance of 8.5 kpc. If the OH (1720 MHz) maser velocity (−12.3 km s^{-1}) is assumed for the body of the Tornado, the kinematic (far) distance to both the OH (1720) MHz maser and SNR candidate is ~ 12 kpc (Frail et al. 1996).

4.2. Properties of G357.63−0.06

The measured properties of the Eye at 1.42, 4.86, and 8.31 GHz from this study are shown in Table 2. As noted in previous studies the Eye has a relatively flat, but slowly rising spectrum below 4.9 GHz (Shaver et al. 1985b; Burton et al. 2002) indicative of an optically thin H II region. Our radio flux measurement at 8.3 GHz is the first to fill the gap between 4.9 GHz and 1.3 mm (upper limit non-detection at 1.3 mm of 1 Jy by Shaver et al. (1985b)). The measured 8.3 GHz flux density of 88 mJy is consistent (within the noise) with an optically thin H II region spectrum assuming $S_\nu \propto \nu^{0.1}$. Studies of the spectral energy distribution of G357.63−0.06 by Shaver et al. (1985b) and Burton et al. (2002) using infrared colors (IRAS and MSX) show that there can be very little contribution from dust at 8.3 GHz, as expected, in agreement with our findings.

The derived parameters of the H II region G357.63−0.06 assuming $d = 8.5$ kpc, $S = 88$ mJy (8.3 GHz flux density), size=6″, and $Y^+ = 0.1$ are: shell radius $Rs = 0.2$ pc, electron density $ne = 1.6 \times 10^3$ cm^{-3}, emission measure $EM = 1 \times 10^6$ pc cm^{-6}, excitation parameter $u = 26.9$ pc cm^{-2}, mass of ionized gas $M_{\rm HII} \sim 1.2$ M$_\odot$, and number of Lyman continuum photons $Nc = 5.7 \times 10^{47}$ photons. The LTE electron temperature of the ionized gas is $T_e \sim 11,000$ K assuming $Y^+ = 0.1$. If we assume that a single star powers the H II region given its shell like morphology (Fig. 2), these parameters indicate that the central star is about O9 or B0 type. These estimates for the parameters of the Eye are similar to those listed by Shaver et al. (1985b) and Burton et al. (2002).

5. CONCLUSIONS

We have unambiguously identified G357.63−0.06 as a Galactic H II region via the discovery of a 8.3 GHz H92α radio recombination line at a velocity of ~ -210 km s^{-1}. Based on this unusually high negative velocity along with new H I absorption data, we show that this source most likely lies near the Galactic Center with a minimum projected distance of 350 pc. Using the radio continuum parameters of G357.63−0.06, we find that the mass of the ionized gas is $M_{\rm HII} \sim 1.2$ M$_\odot$ and that the number of Lyman continuum photons is consistent with this source being powered by a O9 or B0 type star.

Assuming that the OH (1720 MHz) maser discovered by Frail et al. (1996) is associated with the the Tornado (G357.7−0.1) SNR candidate, we also find that the Tornado and Eye are well separated kinematically. Thus the location of the Eye along the symmetry axis of the Tornado, while suggestive of a unique interaction given the Tornado's unusual morphology, is simply due to chance superposition along the line of sight. Additionally, high dynamic range H I absorption data towards the body of the Tornado suggests that it too must lie at least as far away as the Galactic center and most likely at 12 kpc if the OH (1720 MHz) maser velocity is assumed.

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